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Optimization of FAST Electron Gun Beam Parameters Using *ASTRA*

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FAST

The Fermilab Accelerator Science and Technology Facility (FAST) includes a superconducting RF linear electron accelerator which will provide venues for advanced accelerator R&D (AARD) and future experiments like IOTA.

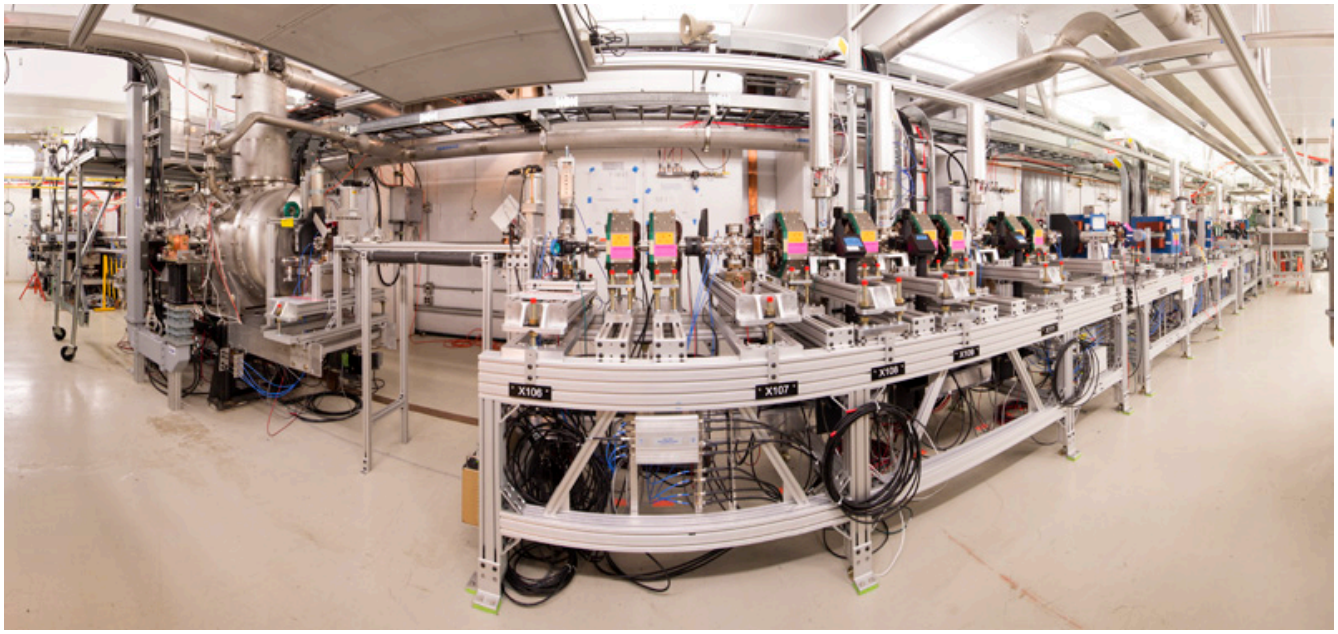


Figure 1: Cyro Module and beam line, FAST Cave Configuration at NML. Photocathode electron gun and toroid monitor to the left, beam travels to the right.

Photoinjector Gun

- RF photocathode electron gun (Cs_2Te)
  - Developed at DESY Zeuthen (PITZ)
- Normal-conducting 1½ cell 1.3 GHz gun
  - Driven by 5 MW klystron
  - Solenoids to focus beam
- Routinely operated at peak gradients of 40-45 MV/m producing an output beam energy of ~5 MeV
- Utilizes a feedback system to regulate temperature to better than ±0.02 °C for beam and phase stability

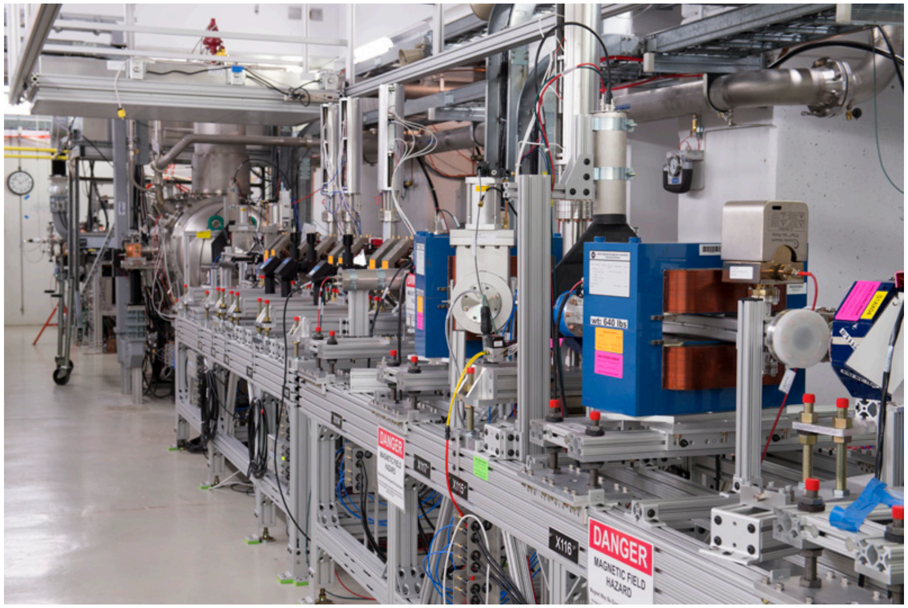


Figure 2: Photoinjector gun, Cyro Module, and beam line.

Photocathode Laser

- Photocathode is a 10 mm diameter polished molybdenum disk
  - Coated with Cs_2Te
  - 7 mm diameter photosensitive area
- 263 nm wavelength laser light directed onto the photocathode
  - Light reflected off of 45° off-axis mirror downstream of the RF coupler
- Injection phase
  - Relative phase of pulses with respect to the RF

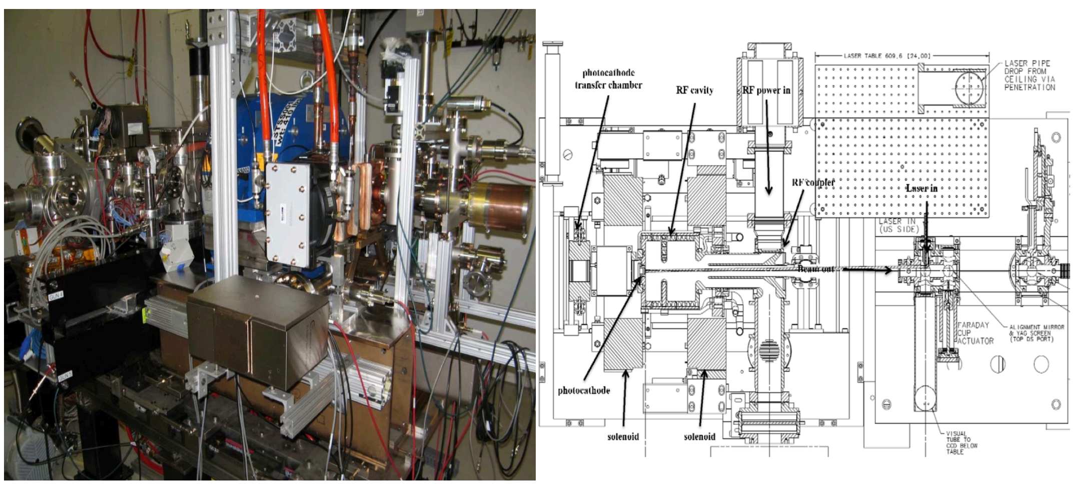


Figure 3: (a) Electron gun installation in the FAST enclosure in August, 2012.
(b) Cross section of gun, solenoids, transfer chamber, downstream instrumentation. Toroid monitor placed before the Faraday Cup to measure beam intensity/charge.

Phase Scan

- In order to optimize gun operation, the RF phase of the gun was varied with respect to the laser across various phase scans
- Accelerated charge measured as a function of launch phase (by a toroid monitor)

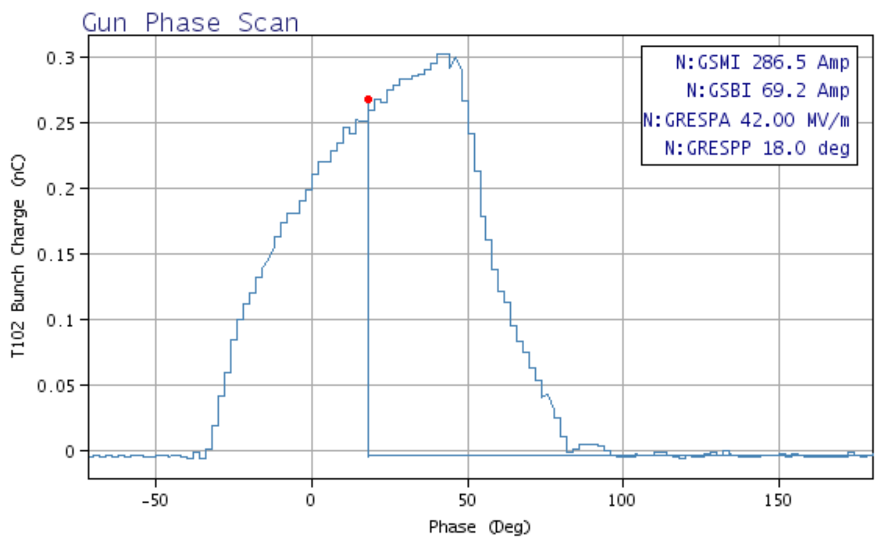


Figure 4: Measured phase scan from the electron gun in FAST. Data taken from a toroid monitor placed 1.186 m downstream from the gun. Plateau in charge is characterized by a significantly steeper slope than was observed at PITZ, which may be caused by a secondary emission of electrons.

Discrepancy

- Faraday Cups and integrating current transformers (ICT) used at PITZ
  - Heat load and secondary emission; sufficiently short/isolated bunch
- However, the phase scans from FAST do not match those from PITZ despite the identical nature of the guns (save for different beam charge)
  - There is no consistent explanation for this discrepancy

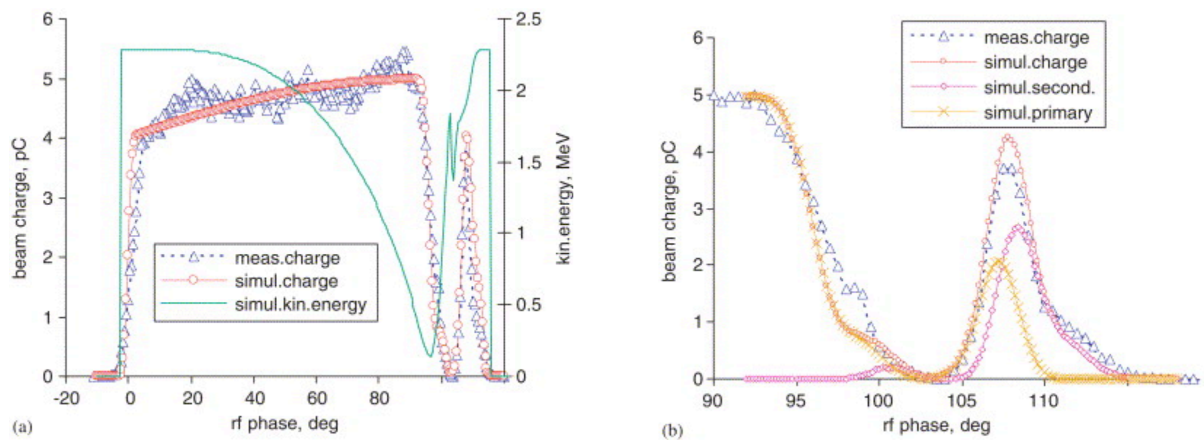
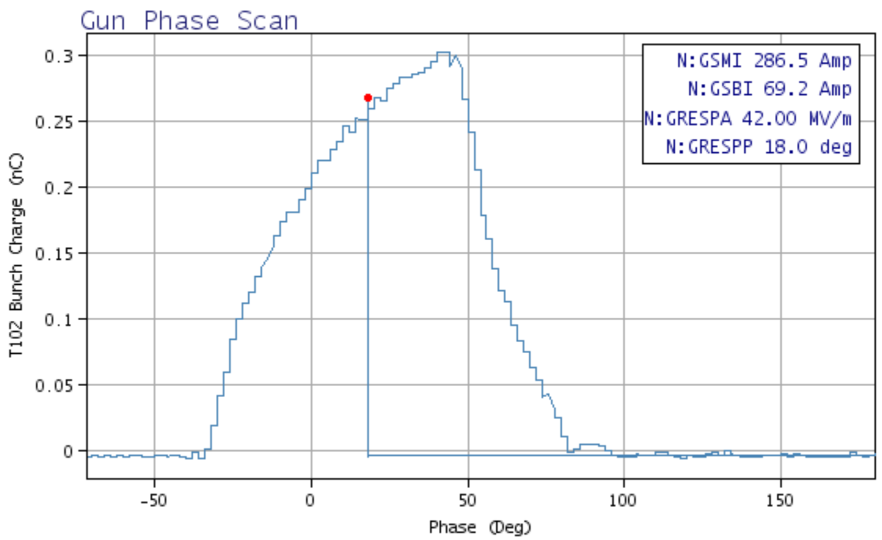
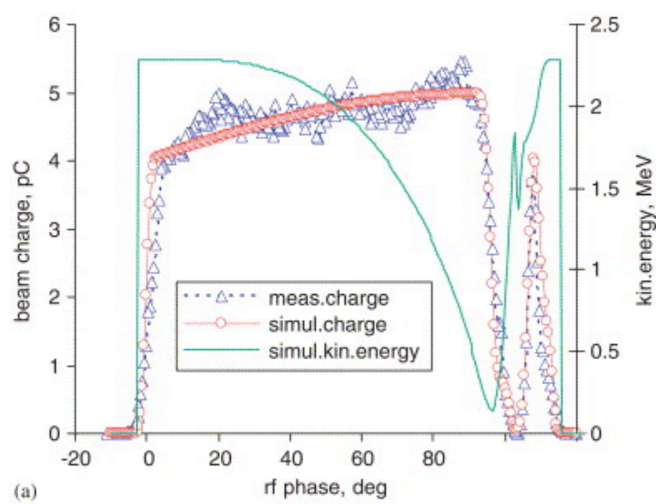


Figure 5: (a) Measured and simulated phase scan (beam charge vs. RF phase). (b) Detailed phase scan for RF phase range ~100–115° [2].

The Problem

- Charge vs. Phase readings had an unexpectedly high peak followed by an abrupt drop-off (maybe related to difference in scale between guns)
- There also existed a smaller peak in charge after the bunch
- Schottky-like effect manifesting itself in the Cs_2Te photocathode.
- Secondary emission of electrons (next slide)
  - Increased slope of plateau





The Schottky Effect

- Describes the lowering of the work function or the potential barrier of a metal by an external electric field
  - Leads to an increased electron emission from the metal
  - Which may explain the unexpected phase scan at FAST
- The charge of a bunch at t_0 is determined as:

$$Q = Q_0 + SRT_{Q_{Schottky}} \cdot \sqrt{E} + Q_{Schottky} \cdot E$$

- E is the combined longitudinal electric field in the centre of the cathode
- Q_0 is the charge of the macro particles as defined in the input distribution (rescaled to fit Q_{bunch})

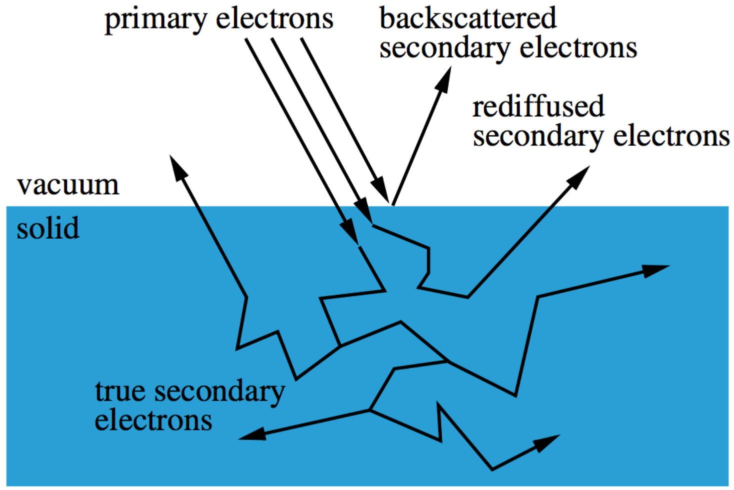


Figure 6: Depiction of secondary emission

Program

- *ASTRA*
  - A Space TRacking Algorithm
  - Written by Klaus Floettmann
- Simulation of datasets through a Monte-Carlo approximation
- However *ASTRA* lacks certain tools/software
  - Parameter modification
  - Parameter optimization
  - Curve-fitting
- Also, *ASTRA* is difficult to automate since it is just an executable

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <math.h>
#include <time.h>
#include <libgen.h>

#define LINE_CHAR 236 //236
#define LINE_BUFSIZE 2+LINE_CHAR

int interface();
int param();
int astra();
int delta();
void plot(double* xData, double* yData1, double* yData2, int dataSize);
FILE* execute(char *bash, char line[LINE_BUFSIZE]);
void writefile(FILE* pipe, FILE* out);
void appendfile(char line[LINE_BUFSIZE], FILE* out);
char* inputstring(char *s);

double lumberphase[12] = {-34, -22, -10, 2, 14, 26, 38, 50, 62, 74, 86, 98};
double lumbercharge[12] = {-0.001064046, 0.099856578, 0.158018127, 0.205068439, 0.235183701, 0.266601682, 0.282234013, 0.265988648, 0.131121278, 0.058323566, 0.002844042, -0.0006809};
double simulation[12];
char globalfile[500];

int main()
{
        //char line[LINE_BUFSIZE];
        //execute("clear", line);

        system("clear");

        //printf("\n----------------------------------------------------------------\n\n");

        printf("\n");

        //printf("CLOCKS_PER_SEC = %i\n", CLOCKS_PER_SEC);

        interface();

        return EXIT_SUCCESS;
}
```

Figure 7: The optimization program, first written in Python, was translated to C in order to more efficiently process large amounts of raw data. Now, it acts as an environment in which bash script and analysis can be run side-by-side.

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Optimization

- Chi-square test for the variance or standard deviation

$$\chi^2 = \sum \frac{(f(x) - S_{sim} \cdot f_{sim}(x,\vec{a}))^2}{\sigma_f^{\;2}} + \frac{(S - S_{sim})^2}{\sigma_S^{\;2}}$$

$$\chi^2 = (f(x) - S \cdot f_{sim}(x,\vec{a}))^2$$

$$\chi = f(x) - S \cdot f_{sim}(x,\vec{a})$$

- Simplified to a delta value (χ), as $\sigma^2 \rightarrow 1$
- *S* is scaling factor between simulation and hardware
- *f(x)* is phase scan function measured experimentally
- $f_{sim}(x, \vec{a})$ is simulated phase scan function

Results

- H_max, H_min; SRT_Q_Schottky, Q_Schottky; SE_d0, SE_Epm, SE_fs
- Correlation between charge and Schottky/secondary emission

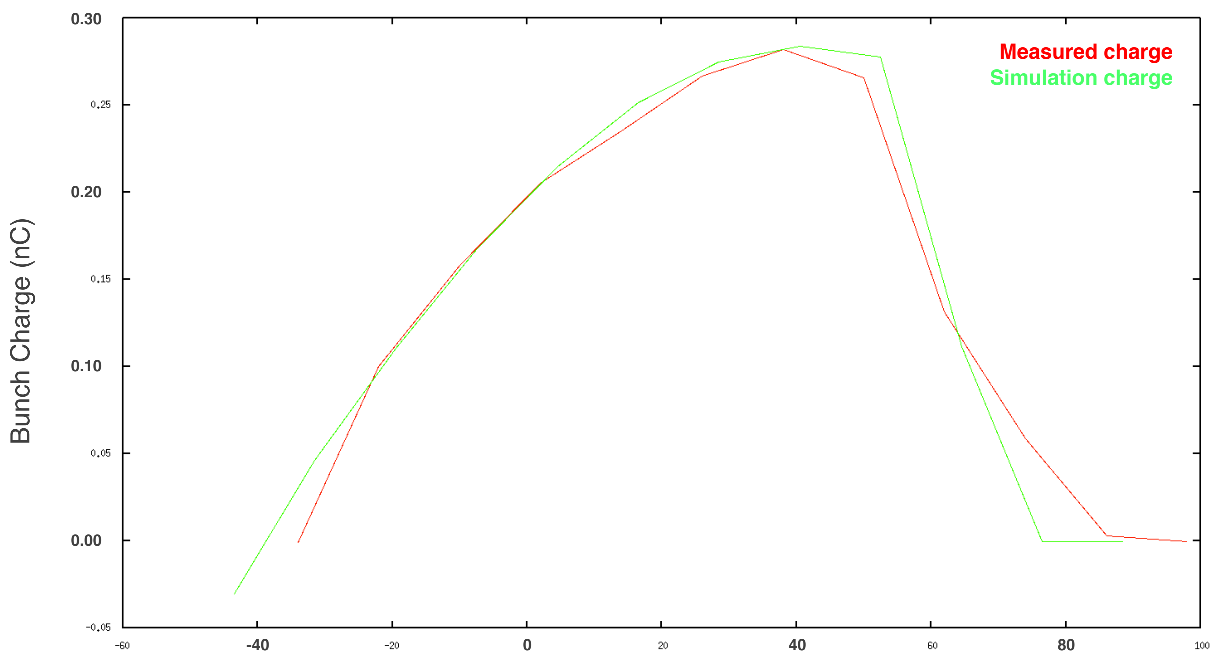

Figure 8: Through the tuning of gun geometry, charge, and Schottky parameters, a relatively accurate approximation of our recorded data was achieved. This lends further evidence towards the hypothesized impact of secondary emission, and hints at a potential hardware scaling factor.

Future Work

- The program developed, as well as the parameters it found, will continue to predict future experimental readings and diagnose issues
- As FAST strives for higher intensities and more bunches, this work will set the stage for future optimization

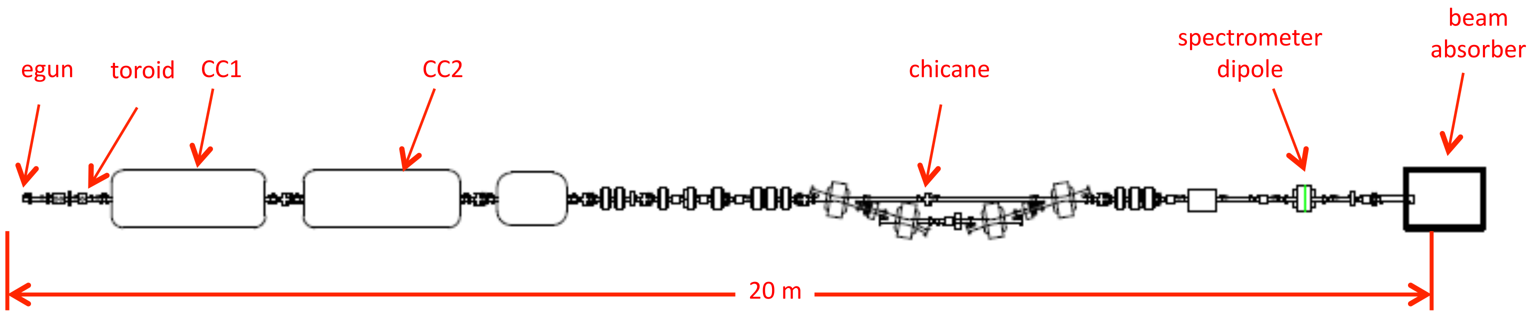

Figure 9: Upstream floor plan of the FAST photoinjector. The beamline is 1.2 m above the floor, the floor is 6.1 m below grade, and the building length is 74 m [1].

Special thanks to Elvin and Dan.

Any questions?